The CUORE experiment

A search for neutrinoless double beta decay

Stefano Dell'Oro

Center for Neutrino Physics,

Virginia Polytechnic Institute and State University

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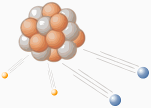
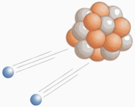
Outline

1. Neutrinoless double beta decay
2. TeO_2 low-temperature detectors
3. CUORE experiment
4. First results from CUORE
5. Background studies
6. Summary



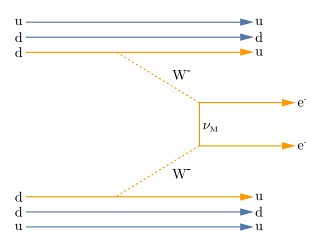
$$(A,Z) \to (A,Z{+}2) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta)$$

$$(A,Z) \to (A,Z{+}2) + 2e^- \quad (0\nu\beta\beta)$$



- *L*-violation: creation of a pair of electrons
  - discovery of $0\nu\beta\beta$
    - $\Rightarrow$ *L* is not a symmetry of the universe
    - $\Rightarrow$ leptons played a part in matter-antimatter asymmetry in the universe (?)
- assuming the ν mass mechanism
  - $\rightarrow$ $0\nu\beta\beta$ key tool for studying neutrinos
    - Majorana or Dirac nature
    - mass scale and ordering

A possible diagram



Adv. High En. Phys. 2016, 2162659 (2016)

L-violation in the SM

- SM language: description of effective (non-renormalizable) operators that respect the gauge symmetry $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$, but violate L
- the new terms can be added to the Lagrangian and Hamiltonian densities

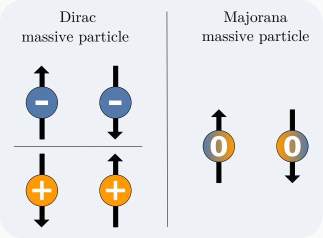
$$\mathcal{H}_{\text{Weinberg}} = \frac{(l_L H)^2}{M} + \frac{l_L q_L q_L q_L}{M'^2} + \frac{(l_L q_L d_R^c)^2}{M''^5} \quad (+ \dots)$$

  - there is only an operator suppressed by one power of the new mass scale (all the others are more strongly suppressed)
  - it is the operator that generates the Majorana neutrino masses

if the scale of new physics is much higher than the electroweak scale,
it is reasonable to assume **Majorana neutrinos** to be
the **mediators of an L-violating process** such as $0\nu\beta\beta$

- New theory for massive and real fermions (E. Majorana, 1937)
  - $\chi = C\bar{\chi}^t \quad \left(\bar{\chi} \equiv \chi^\dagger \gamma_0, \quad C\gamma_0^t = 1\right)$
  - $\mathcal{L}_{\text{Majorana}} = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m)\chi$
  - $\chi(x) = \sum_{\mathbf{p},\lambda} \left[a(\mathbf{p}\lambda)\ \psi(x;\mathbf{p}\lambda) + a^*(\mathbf{p}\lambda)\ \psi^*(x;\mathbf{p}\lambda)\right]$

    $\rightarrow \quad \forall \mathbf{p}$, 2 helicity states: $|\mathbf{p}\uparrow\rangle$ and $|\mathbf{p}\downarrow\rangle$
  - could fully describe massive neutrinos (G. Racah)



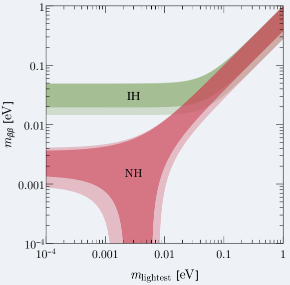
- the Majorana hypothesis can be implemented in the SM
  - $\chi \equiv \psi_L + C\bar{\psi}_L^t \quad \rightarrow \quad \psi_L = P_L\ \chi \equiv \frac{(1-\gamma_5)}{2}\ \chi$ (*usual* field)
- L will be violated by the presence of Majorana mass
  - $\mathcal{L}_{\text{mass}} = \frac{1}{2}\sum_{\ell,\ell'=e,\mu,\tau} \nu_\ell^t\ C^{-1} M_{\ell\ell'}\ \nu_{\ell'} + h.c. \quad \rightarrow \quad 0\nu\beta\beta$ proportional to $|M_{ee}|$

Effective Majorana mass

- $m_{\beta\beta}$ is the key quantity in the $0\nu\beta\beta$
  - absolute value of **ee-entry** of ν mass matrix
  - $m_{\beta\beta} \equiv |M_{ee}| = \left| \sum_{i=1,2,3} e^{i\xi_i} \, |U_{ei}^2| \, m_i \right|$
  - $U \equiv U|_{osc.} \cdot \mathrm{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
    - 1 CP-violating + 3 **Majorana phases**
    - U **mixing matrix** of oscillation analysis
  - only two phases play a *physical* role

$m_{\beta\beta}$ vs. m_{lightest}

Phys. Rev. D 90, 033005 (2014)



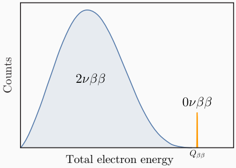
- $m_{\beta\beta} = \left| e^{i\alpha_1} \cos^2\theta_{12} \cos^2\theta_{13} m_1 + e^{i\alpha_2} \cos^2\theta_{13} \sin^2\theta_{12} m_2 + \sin^2\theta_{13} m_3 \right|$

An **experimental measurement** of the $0\nu\beta\beta$ half-life corresponds to

a **horizontal band** in the ($m_{\beta\beta}$ vs. m_{lightest}) plot

Experimental search for $0\nu\beta\beta$

- the search for $0\nu\beta\beta$ relies on detection of the **2 emitted e$^-$**
  - monochromatic peak at $Q_{\beta\beta}$
  - smearing due to finite energy resolution



- the observable is the decay **half-life** $t^{0\nu}_{1/2}$ of the isotope
  - the experimental sensitivity corresponds to the maximum signal that can be hidden by the background fluctuations $n_B = \sqrt{M\,T\,B\,\Delta}$

$$t^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \sqrt{\frac{M\,T}{B\,\Delta}}$$

M = detector mass, T = measuring time, B = background level, Δ = energy resolution

- the information on the **neutrino mass** can be extracted

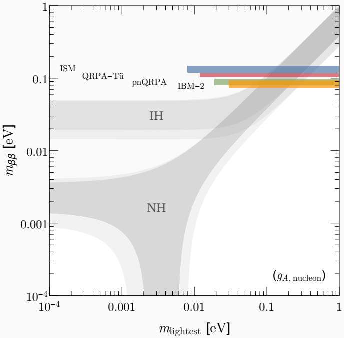
$$\left[t^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,\frac{m^2_{\beta\beta}}{m^2_e}$$

  - $G_{0\nu}$ = **Phase Space Factor** (atomic physics)
  - $\mathcal{M}$ = **Nuclear Matrix Element** (nuclear physics)
  - $m_{\beta\beta}$ = **effective Majorana mass** (particle physics)

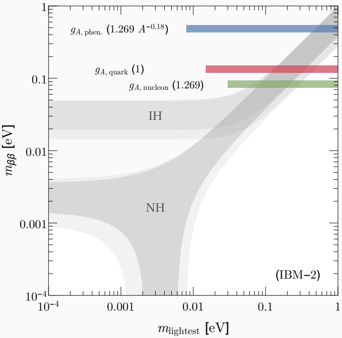
$$m_{\beta\beta} \leq \frac{m_e}{\mathcal{M}\sqrt{G_{0\nu}\,t^{0\nu}_{1/2}}}$$

Implication of theoretical uncertainties

- most stringent experimental limit: $1.07 \cdot 10^{26}$ yr @ 90% C. L. (^{136}Xe, KamLAND-Zen)
- $t^{0\nu}_{1/2} \propto \mathcal{M}^{-2} = g_A^{-4}\ \mathcal{M}_{0\nu}^{-2}$
- different NMEs / fixed g_A
- different g_A / fixed NMEs



$74\ \text{meV} < m_{\beta\beta} < 149\ \text{meV}$

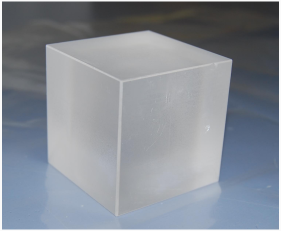


$74\ \text{meV} < m_{\beta\beta} < (149)\ 542\ \text{meV}$

large uncertainties from **nuclear physics** (especially true value of $\boldsymbol{g_A}$)

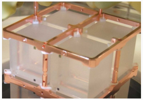
A powerful search has to aim at the optimal
isotope + detector technique combination

- ^{130}Te is an ideal candidate for the $0\nu\beta\beta$ search
  - $Q_{\beta\beta}$ moderately high: (2527.515 ± 0.013) keV (between the ^{208}Tl peak and Compton edge)
  - large natural abundance: $(34.167 \pm 0.002)\%$
- Tellurium dioxide, TeO_2, suitable for the use in cryogenic particle detectors
  - high Debye temperature: $\Rightarrow$ small heat capacity
  - thermal expansion close to copper
- production of **high-quality crystals**
  - large mass: ~ 750 g ($5 \times 5 \times 5$ cm^3)
  - scalability of detector arrays
- very **low radioactive contamination**
  - bulk: 10^{-14} g/g for both U and Th
  - surface: $< 10^{-9}$ Bq cm^{-2} for both U and Th

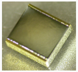

CUORE crystal

Working principle

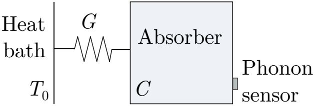
- bolometers detect the **phonon** contribution of the energy released
  - large fraction of the total energy
  - ionization/excitation → · · · → phonons
  - measured via **temperature variation**



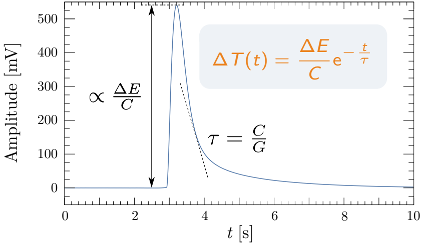
- $\Delta T = \Delta E / C$
  - **low C**: $C \downarrow \;\Rightarrow\; \Delta T \uparrow$
  - **very low T**
    - Debye law: $C \propto (T/\Theta_D)^3$
    - thermal fluctuations $\propto T^2\,C$
- temporal evolution: $\tau = C/G$
- NTD Ge thermistor
  - $R = R_* \, \exp\,(T_*/T)^{1/2}$



Simplified thermal model

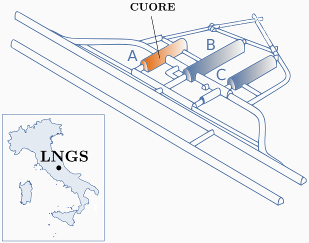


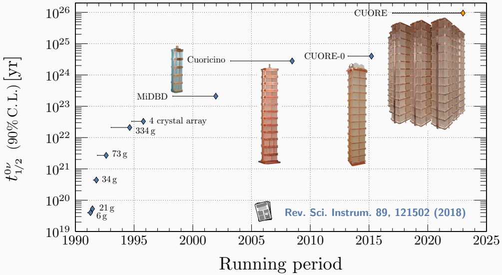
- an absorber with heat capacity C
- (connected to) a heat bath @ constant T_0
- (through) a thermal conductance G

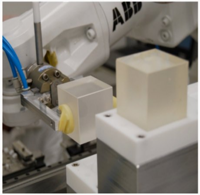
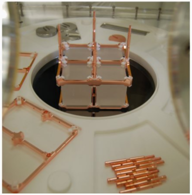
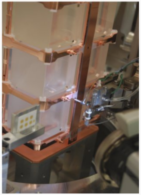


- LNGS $\rightarrow$ ideal place to search for $0\nu\beta\beta$
  - 3600 m w. e. overburden
  - μ: $3 \cdot 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ / n: $4 \cdot 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- dedicated facilities to run bolometric detectors
  - Hall A dilution refrigerator (1989)
    - crystals (1991 – 1995)
    - MiDBD (1998 – 2001)
    - Cuoricino (2003 – 2008)
    - CUORE-0 (2013 – 2015)
  - CUORE cryostat (2016)
    - **CUORE** (from 2017)

30-year long history of measurements

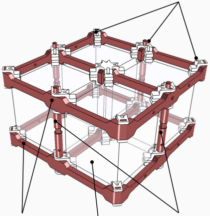




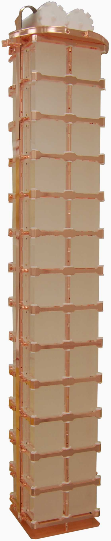
J. Instrum. 11, P07009 (2016)

- strict **material selection**
- high-standard **surface cleaning protocols** for detector components
  - crystal etching + lapping @ SICCAS (China)
  - magnetron plasma cleaning for Cu frames @ LNL of INFN
- **Rn exposure minimized** $\Rightarrow$ avoid surface re-contamination
  - all operations performed in N_2 sealed glove boxes
- **semi-automatic** system for sensor **gluing**
  - highly-reproducible
- **contact-less** approach in **tower assembly & bonding**



First CUORE tower: the CUORE-0 detector

- CUORE-0 was the first CUORE-like tower produced
  - 52 TeO_2 $5 \times 5 \times 5\,cm^3$ (750 g each)
  - 13 4-crystal floors
  - total detector mass: 39 kg (10.9 kg of ^{130}Te)
- **proof of concept** of CUORE detector
  - validation of the CUORE cleaning and assembly protocol
  - test of the CUORE DAQ and analysis framework
  - check of the radioactive background reduction
- **standalone experiment** (Mar 2013 – Sep 2015)
  - improved bolometric performance w. r. t. Cuoricino
    - uniformity of the single detector response
    - high energy resolution: (4.9 ± 2.9) keV @ $Q_{\beta\beta}$
  - measurement of the $2\nu\beta\beta$: $t^{2\nu}_{1/2} = (8.2 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})) \cdot 10^{20}$ yr
  - new limit on the ^{130}Te $0\nu\beta\beta$: $t^{0\nu}_{1/2} > 4.0 \cdot 10^{24}$ yr @ 90% C. L.



Phys. Rev. Lett. 115, 102502 (2015)

CUORE detector

CUORE: Cryogenic Underground Observatory for Rare Events

- largest bolometric detector ever built by a factor 10
  - 19 towers × 13 floors × 4 crystals = 988 bolometers
  - 1 tonne detector mass: 330 kg Cu + 742 kg TeO_2

    → 206 kg of ^{130}Te
- design goals on performance
  - 5 keV FWHM energy resolution @ 2615 keV
  - 0.01 c keV^{-1} kg^{-1} yr^{-1} in the $0\nu\beta\beta$ region
- physics program: **search for $0\nu\beta\beta$ of ^{130}Te**
  - measurement of $2\nu\beta\beta$ half-life + Te rare decays
  - search for DM candidates (WIMPs, axions, . . .)
  - study of the bolometric thermal behavior
  - investigation of background for

    a next generation $0\nu\beta\beta$ experiment

CUORE requires a **dedicated cryogenic system** in order to be operated as a bolometer

A 10 mK infrastructure for large bolometric arrays

- the **design** of the CUORE cryostat had to satisfy **very tight requirements**
  - large **experimental volume** for detector + shielding of $\sim$ 1 m^3
  - **base temperature** for optimal operation of NTDs, i. e. down to 10 mK
  - **low radioactive background** from the cryogenic apparatus,

    compatible with goal of 0.01 c keV^{-1} kg^{-1} yr^{-1} at $Q_{\beta\beta}$
  - **high system reliability** to guarantee long-term operation
  - **response to seismic events**

    (LNGS are located in a seismic sensitive area)

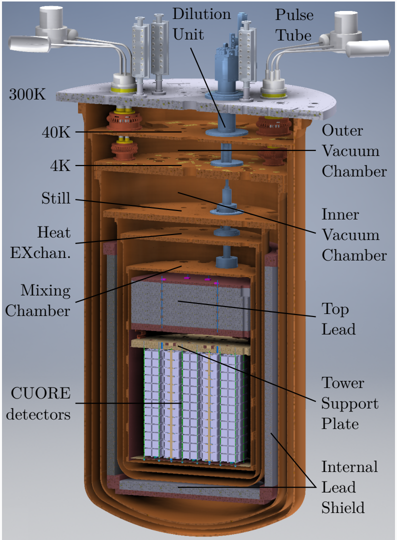
- custom cryogen-free cryostat
- only a few construction materials acceptable
  - use of Cu OFE/Cu NOSV for plates and vessels
  - more than 6.5 t of lead shielding integrated in the structure

Cryostat configuration

- 6+1 thermal stages
  - 300 K @ ambient temperature
  - 40 K @ PT first stage temperature
  - 4 K @ PT second stage temperature
  - Still @ 800 mK
  - HEX @ 50 mK
  - MC @ base $T < 10$ mK
  - TSP @ stabilized working T
- 2 vacuum chambers
- Fast Cooling System +

  5 Pulse Tubes + custom Dilution Unit
- 2 internal lead shields
  - Top Lead (2.7 tonnes)
  - side + bottom (ILS, 4.5 tonnes)
- 2 calibration systems
  - internal / external sources

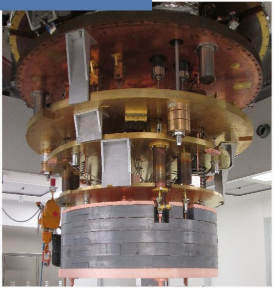
arXiv:1904.05745 [physics.ins-det]



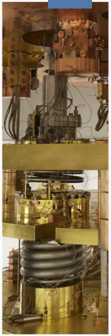
We actually built it!

CUORE

Plates + Top Lead

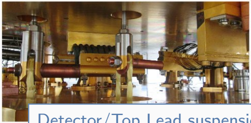


DU



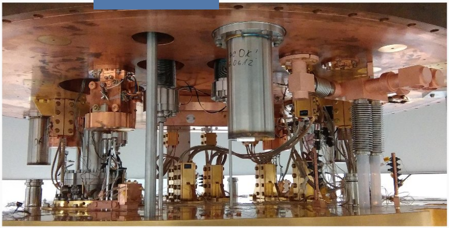
PT

Superinsulation

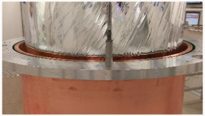


Detector/Top Lead suspensions

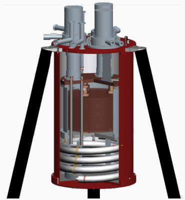
Inside the IVC

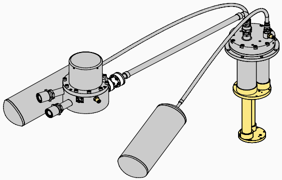


Vessels

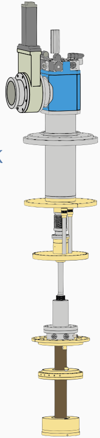


- Fast Cooling System
  - pre-cools IVC mass (+ detector) down to $\sim$ 50 K
  - cold He gas injected inside IVC +
    forced circulation inside external cooling circuit
  - keeps cool down time $\sim$ 20 days



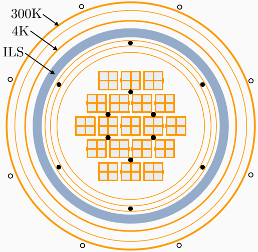


- Pulse Tubes (5 Cryomech PT415-RM)
  - maintain T of 40 K and 4 K stages
  - cooling power (1 unit): 0.5 W @ 3.5 K / 20 W @ 35 K
  - mechanical vibrations (He pressure waves, motors)
    $\rightarrow$ suppression / reduced transmission



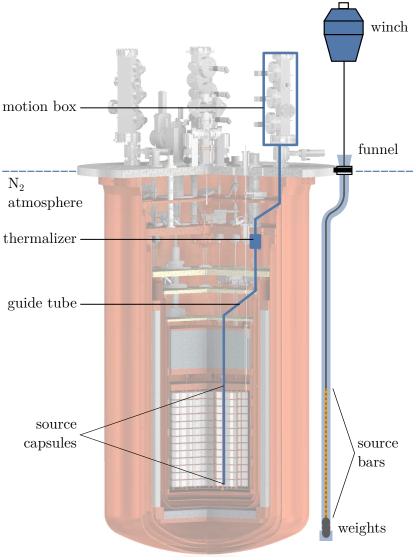
- Dilution Unit (custom Joule-Thomson DU by Leiden Cryogenics)
  - maintains stable base T for inner stages and operating detector T
  - high cooling power: 3 μW @ 10 mK / 125 μW @ 50 mK / 3 mW @ 800 mK

- Internal calibration
  - sources deployed into the cryostat
  - thermalization of source strings
  - capsules with thoriated tungsten wires
- External calibration
  - strings run outside 300 K vessel
  - thoriated tungsten bars + Co sources



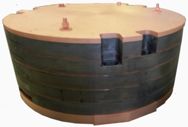
Nucl. Instrum. Meth. A844, 32 (2017)

Internal/external calibration systems

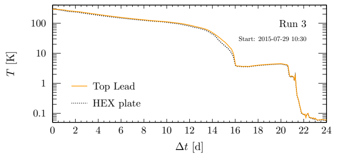


Lead shields

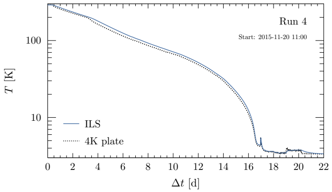
- Top Lead
  - 30 cm thick
  - 2.1 t Pb + 0.35 t Cu
  - thermalized @ 50 mK



Top Lead thermalization



ILS thermalization



- Internal Lead Shield
  - 6 cm thick
  - 4.5 t Pb + 0.86 t Cu
  - thermalized @ 4 K
  - **Roman lead**

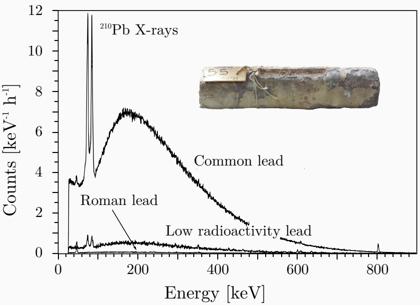
- External Lateral Shield (70 t Pb + 6 t polyethylene)
  - side: 18 cm polyethylene + 2 cm H_3BO_3 + 25 cm Pb
  - bottom: 20 cm borated polyethylene + 25 cm Pb

The CUORE Roman lead shield (I)

- lead is a good shielding material
- *but*: presence of ^{210}Pb ($t_{1/2} = 22.3\,\text{yr}$)
  - $^{210}\text{Pb} \xrightarrow{\beta^-} {}^{210}\text{Bi} \xrightarrow{\beta^-} {}^{210}\text{Po}$
  - bremsstrahlung → low-E background

The CUORE ILS (4.5 tonnes) is made of **ancient Roman lead**: only a measured upper limit of $4\,\text{mBq}\,\text{kg}^{-1}$ for ^{210}Pb

Nucl. Instrum. Meth. Phys. B 142, 163 (1998)



The ingots

- lead extracted from the Cartagena ore district (Spain)
- production during the late Republican Age (I century BCE)
  - ∼ 80% by the company SOC·MC·PONTILIENORVM·M·F
- retrieved from a shipwreck close to Mal di Ventre Island (Sardinia)
- ∼ 270 over 983 lead pigs used in low bkg experiments @ LNGS

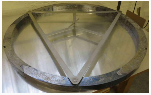
The CUORE Roman lead shield (II)

Long series of careful operations

- removal of the cartouches


- ingot surface cleaning (cryoblasting)

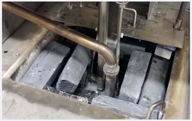
- **casting** at MTH foundry (Germany)
- casted parts check and assembly test

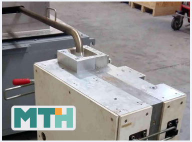



- vacuum sealing into plastic bags

Working @ MTH

- only CuAl and SS tools
- new furnace, pump and mold
- no release agent / chemicals
- only dry cuts
- **molten lead under constant N_2 flow**
- always gloves with casted parts

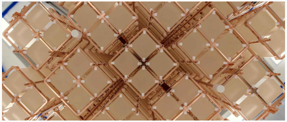


paper in preparation

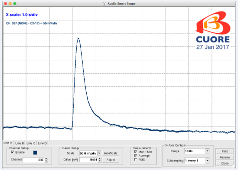
- tower assembly (Sep 2012 – Jul 2014)
- cryostat commissioning

  (Aug 2012 – Mar 2016)
- detector installation (Jul – Aug 2016)

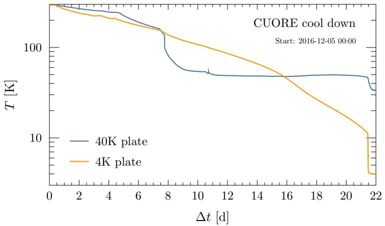


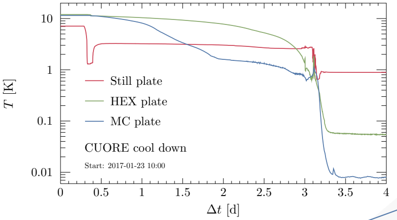
- cool down (Dec 2016 – Jan 2017)

First observed event



CUORE cool down

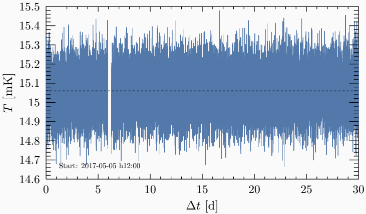




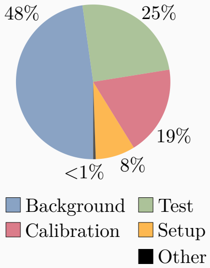
$T_{MC} = 6.8$ mK

CUORE first science run

- start of Physics data-taking (Apr 2017)
  - working ***T*** set to **15 mK**
  - **Dataset 1**: 3 weeks of physics data
  - further optimization campaign
  - **Dataset 2**: 4 weeks of physics data



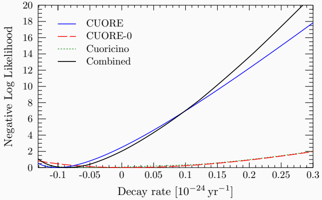
- collected exposure for 86.3 kg yr of TeO_2 (24.0 kg yr of ^{130}Te)



Operational performance

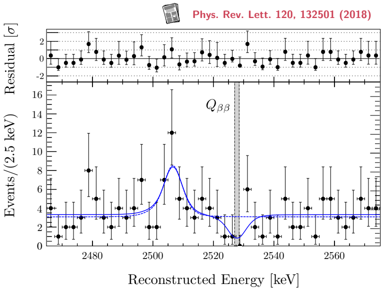
- **99.6%** of channels active (984/988)
- energy resolution at $Q_{\beta\beta}$ of **7.7 keV** FWHM
- signal efficiency of ∼ **80%**
- . . . room for improvement ⇒ **maximize sensitivity**
  - cryogenic stability
  - calibration/background ratio

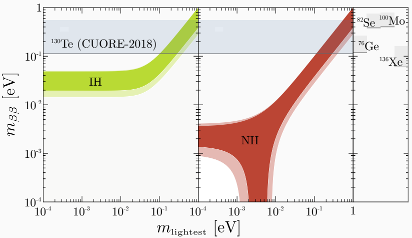
- no peak found at $Q_{\beta\beta}$
- **bkg index** consistent with expectations:
  $(1.4 \pm 0.2) \cdot 10^{-2}\,\mathrm{c\,keV^{-1}\,kg^{-1}\,yr^{-1}}$
- median statistical sensitivity:
  $t^{0\nu}_{1/2} = 7.0 \cdot 10^{24}$ yr @ 90% C. L.
- **combined limit** on ^{130}Te:
  $t^{0\nu}_{1/2} > 1.5 \cdot 10^{25}$ yr @ 90% C. L.



- limit on the effective Majorana mass:
  $m_{\beta\beta} > (110 - 520)$ meV

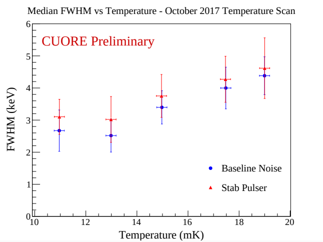
ROI spectrum





Present status

- partial warm up to 100 K (Nov 2017 – Mar 2018)
  - replace a set of gate valves & fix a minor leak
- **2nd Physics data-taking** (Jul – Sep 2018)
  - new operating $T = 11$ mK
  - reduction of noise from PTs
  - resolution unchanged
  - $>$ doubled statistics



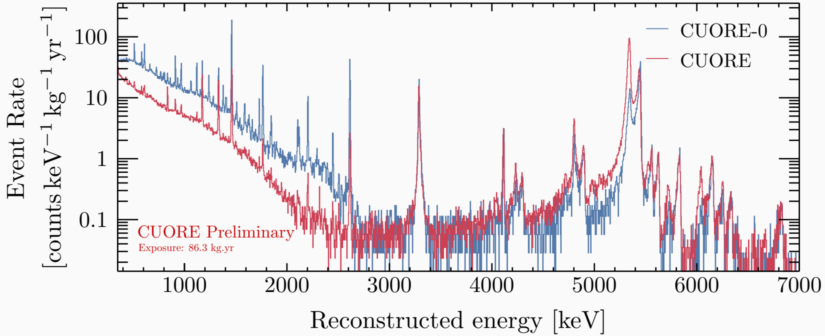
- major maintenance (winter 2018/19)
  - partial warm up to 100 K
  - improved DU circuit
  - installed **external calibration system**
  - fixed leaking PT
- **3rd Physics data-taking** (from Mar 2019)
  - higher duty cycle
  - 2 new datasets. . . data-taking on-going

New results soon!

- updating $0\nu\beta\beta$ analysis
- low-E studies
- finalizing bkg studies
- . . . getting ready for TAUP

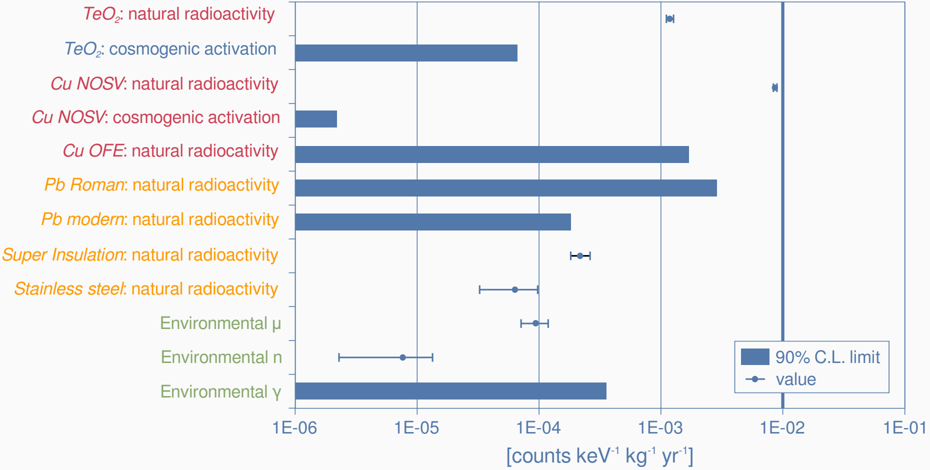
stay tuned!

Understanding the CUORE background



- in general, background consistent with expectations
  - γs significantly reduced
  - most αs compatible with CUORE-0
- ^{210}Po excess likely from shallow contamination in copper around the detectors
  - still working on it
  - estimated contribution to ROI at level of 10^{-4} c keV^{-1} kg^{-1} yr^{-1}

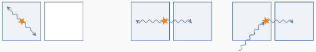
Eur. Phys. J. C, 77, 543 (2017)



cosmogenic activation Te CUORE-0 bkg model material screening environmental fluxes

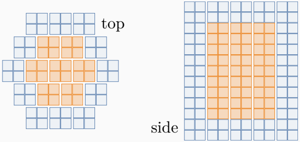
Modeling the background

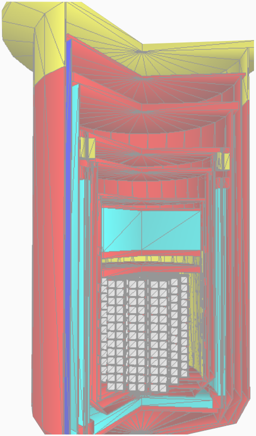
- simulation of contamination from different cryostat components with **Geant4 MC**
- background sources identified/ascribed to different locations in experimental setup
- inputs of MC
  - coincidence analysis, gamma peaks, alpha peaks
  - radio-assay measurements, data from neutron activation
- splitting data
  - multiplicities: sensitive to different types of bkg



...

  - inner and outer layers: utilize self shielding by the outer layers

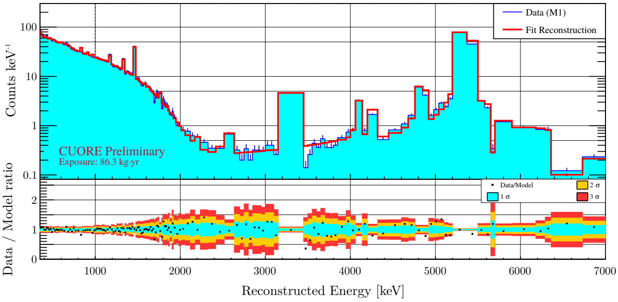




Fit of the CUORE background

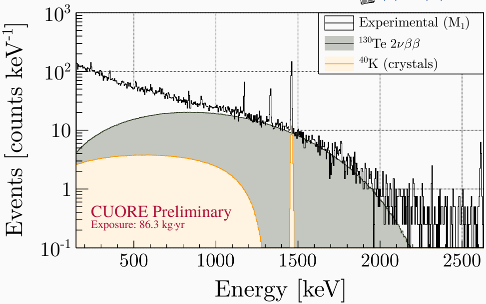
- used data collected in summer 2017: 86.3 kg yr of TeO_2 exposure
- ∼ 60 independent parameters for possible contamination contributing to bkg model
    - bulk and surface (for near elements) contamination
- large Bayesian Fit to data
    - flat priors on all parameters (except muons which come from cosmogenic analysis)

Multiplicity 1 - Inner layer



Observation of the ^{130}Te $2\nu\beta\beta$

paper in preparation



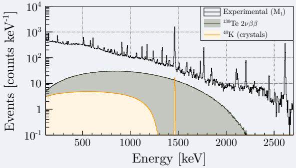
CUORE: $t_{1/2}^{2\nu} = (7.9 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})) \cdot 10^{20}$ yr

CUORE-0: $t_{1/2}^{2\nu} = (8.2 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})) \cdot 10^{20}$ yr

NEMO-3: $t_{1/2}^{2\nu} = (7.0 \pm 0.9\,(\text{stat.}) \pm 1.1\,(\text{syst.})) \cdot 10^{20}$ yr

Comparison with CUORE-0

Eur. Phys. J. C 77, 13 (2017)



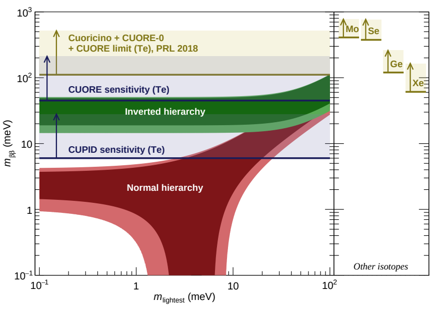
- **CUORE-0**
  $2\nu\beta\beta$ spectrum accounts for $\sim 20\%$ of counts in $(1-2)$ MeV range
- **CUORE**
  $2\nu\beta\beta$ spectrum dominates for nearly all events in $(1-2)$ MeV range

Looking ahead

- CUORE will continue to be one of the most sensitive searches for $0\nu\beta\beta$ over the next years
- final expected sensitivity (5-year live time): $t^{0\nu}_{1/2} = 9 \cdot 10^{25}$ yr @ 90% C. L.

. . . and **beyond** CUORE: CUPID = CUORE Upgrade with Particle IDentification

- next-generation $0\nu\beta\beta$ experiment
  - covering the **IH region**
  - sensitivity: $t^{0\nu}_{1/2} \sim 5 \cdot 10^{27}$ yr
- about **1k** enriched light-emitting **bolometers** inside the CUORE cryostat
- close to zero background: $\mathbf{0.1\,c\,t^{-1}\,yr^{-1}}$
  - active rejection of α *vs.* β/γ events
- today, **worldwide effort** to demonstrate readiness for a tonne-scale bolometric experiment with double readout



to be continued. . .

Summary

- $0\nu\beta\beta$ is a unique tool to study L-violation and neutrino masses
- TeO_2 bolometers meet the requirements for a powerful search
  - a long series of experiments has been carried out at LNGS over the years
- the search with CUORE has begun
  - with first data release, CUORE set the most stringent limit on the $0\nu\beta\beta$ half-life of ^{130}Te

    $$t^{0\nu}_{1/2} > 1.5 \cdot 10^{25}\ \text{yr @ 90\% C. L.}$$

  - most precise measurement of the ^{130}Te $2\nu\beta\beta$ half-life

    $$t^{2\nu}_{1/2} = (7.9 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})) \cdot 10^{20}\ \text{yr}$$

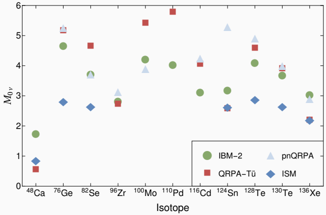
  - we have restarted physics data taking
  - new data release soon!
- R&Ds / new projects are taking place in view of a next generation bolometric experiment

Thank you!

CUORE Collaboration - LNGS (Italy), May 2018

Assessing the uncertainties

- estimate of the uncertainties on PSFs/NMEs is crucial to constrain $m_{\beta\beta}$
- theory of **PSFs** is known / mostly computational difficulties $\Rightarrow \sim$ **7%**
- quite large uncertainties for the **NMEs**
  - different theoretical models: QRPA, IBM-2, ISM, ...
  - error on individual calculations of $\sim 20\%$
  - still **hard to give an overall estimate**
  - calculations *vs*. rates discrepancies $\gg 20\%$ for known processes (β, EC, $2\nu\beta\beta$)



- $\mathcal{M} \equiv g_A^2\,\mathcal{M}_{0\nu} = g_A^2 \left(\mathcal{M}_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 \mathcal{M}_F^{(0\nu)} + \mathcal{M}_T^{(0\nu)} \right)$
  - significant effect of axial coupling constant
    - uncertainty on its values $\Rightarrow$ larger uncertainty on $\mathcal{M}$
  - the value of g_A in the nuclear medium is **not reliably known**
    - from 1.27 (free nucleon) to < 1 (quenching)

Interplay with searches at accelerators

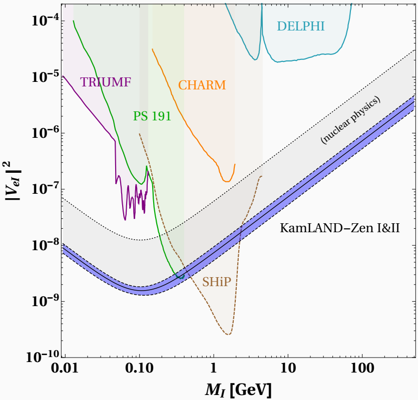
- observation of a $0\nu\beta\beta$ signal in the next generation of experiments
  $\rightarrow$ other mechanisms with faster decay rate at work, e. g. Type I Seesaw neutrinos

- $$\left[t^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} \left| \mathcal{M}_{0\nu} \sum_{i=1}^{3} U^2_{ei} \frac{m_i}{m_e} + \mathcal{M}_{0N} \sum_I V^2_{ei} \frac{m_p}{M_I} \right|^2$$

- $$\left| \sum_I \frac{V^2_{eI}}{M_I} \right| < \frac{1.2\cdot10^{-8}}{m_p} \left[\frac{67}{\mathcal{M}_{Xe}}\right] \left[\frac{1.1\cdot10^{26}\,\text{yr}}{t^{1/2}_{0\nu}}\right]^{1/2}$$

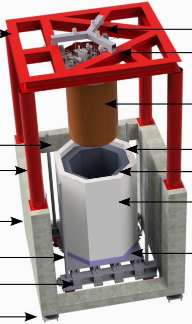
- theoretical uncertainties (mostly nuclear physics) play a significant role

Rep. Prog. Phys. 79, 124201 (2016)



Cryostat support structure

- double function
  - mechanical support of all cryostat parts
  - isolate cryostat from hut + external world ($\rightarrow$ noise)
- design subjected to **deep seismic analysis**
  - 4 seismic insulators
  - concrete walls + beams
  - steel reinforcement brace
  - sand-filled columns
  - grid of steel beams
  - *Minus K* insulation system



CUORE hut (Hall A @ LNGS)